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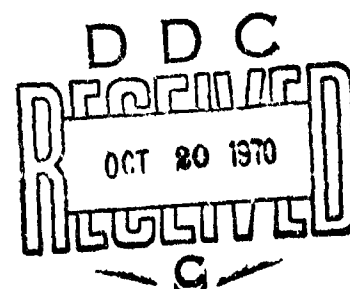
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Earth Environmental Noise Fields

F.A. CROWLEY
H.A. OSSING

United States Air Force

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Abstract

A new method to approach earth noise field problems in inertial component testing is presented. This method is considered superior to accepted "quiet site" and "motion suppression structure" techniques. The approach is to describe earth noise by determining: (1) the class of the random motion; (2) the level of motion; (3) the mode of motion; and (4) the component relationships. The efficacy and rationale of this technique is demonstrated in an experiment that results in the removal of earth noise error terms from gyro data.

Earth Environmental Noise Fields

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It is now widely recognized t' ' further advancements in the accuracy of inertial guidance systems are conditioned on properly resolving between errors due to accelerometer and gyro deficiencies and those caused by false assumptions about the nature of the test environment. No longer can component performance tests treat the earth as a rigid body spinning on a fixed axis. Indeed, as we look ahead, we find that the earth is a noisy medium for inertial component testing.

Historically, the problem of earth noise in inertial component tests has been dominated by two opposing test philosophies. At the one extreme there are those who would wish to avoid earth noise problems by seeking out stable, low-motion sites for locating test facilities. At the other extreme, there are those who would rely solely on motion attenuation/compensation structures to obtain a permissible test environment. To these two approaches we now add a third, namely the suppression of earth noise terms through optimum processing of auxiliary earth motion measurements. In effect, we seek to treat earth noise as an extension of shake table testing. We propose to do this by measuring earth noise and then allowing for it in component tests.

AFCRL was introduced to the problem of earth noise in inertial components by the NASA Electronics Research Center (ERC), formerly located in Cambridge. It was NASA's attitude that the advantage of being an abutter to MIT outweighed

the difficulties of constructing structures for attenuating/compensating in the high noise levels at its Cambridge site. In contrast, the Air Force sought to forestall, at least temporarily, earth noise problems by going to a seismically quiet site in New Mexico.

In their extremes, both test philosophies are found wanting. Those that sought out low noise environments discovered that test facilities bring with them motion sources that degrade their once "quiet" site. In turn, advocates of motion-suppressing structures have met with only partial success in suppressing earth noise over the pass band of interest.

Earth noise in component testing can be defined as those unknown or unaccounted motions of the test environment that affect inertial hardware performance. The total motion at a test facility can be conceived as the composite motion due to propagating waves, deformations due to loading, local thermal stresses, alterations in ground water, etc., as well as to large scale phenomena like wobble of the earth's axis and tectonic processes. For our part, we have concentrated our efforts on only a part of the problem—namely, motions between 0.1 and 10.0 Hz. This choice of frequencies constitutes a troublesome crossover zone between the effective bands of passive and active motion reduction structures conceived by ERC-NASA, our original sponsor.

The motions at the bulk of the sites that we have studied support the thesis that earth noise in the band 0.1 to 10.0 Hz takes the form of propagating waves that are excited by a large number of independent random motion sources. The features of these motions relative to testing are determined by the behavior and distribution of the sources as well as by the ground transmission characteristics of an area. Measured distributions of the motion (Figure 1) have the form of a normal distribution. Normally distributed variates will result when the measurements are the sum of a large number of independent random sources. The temporal attributes of normal motion processes are well described in terms of correlation and/or spectral estimates.

Figure 2 is a set of spectra formed on data taken at the ERC-NASA site, over a period of one week. The levels of measured spectra are found to be strongly locked to the work week cycle for this urban area. In geological cross secti ,
the site consists of an alluvial, slow-speed layer overlying a hard, high-speed rock. For such layering, we can expect strong ground resonances to occur. The observed narrow band spectra appear to be an attribute of man-made sources and resonant structure of the site. When man-made motion sources drive local ground resonances, large motions result. The motion levels found at this site are several orders of magnitude larger than those measured at local, surburban, hard-rock areas. Our motion statistics can be treated as periodically stationary for this locale; that is, correlations are insensitive to discrete shifts in their time of estimation.
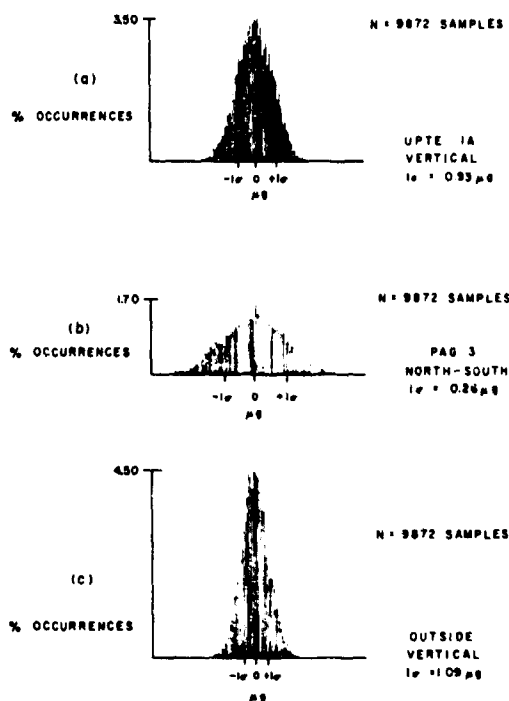
Figure 1. Acceleration Probability Density

The assessment of earth motion in inertial component tests calls for establishing two other properties of the motion environment in addition to class and level, namely the mode and the organization of the motion. By mode, it is meant that we must differentiate between rotational and translational motions. In turn, estimates of organization call for the strength of amplitude/phase relations between components. Let us first consider the problem of isolating rotations and translations. The problem is relevant to systems using single-degree-of-freedom (SDF) gyros. SDF gyro-based Azimuth Laying Sets (ALS) are now being deployed as the prime azimuth control for the Minuteman fleet.

The problem of isolating rotations and translations lies in the fact that our measuring instruments, pendulous seismometers, respond equally well to both rotations and translations. To overcome this ambiguity in measurement, we require the combination of four seismometers arranged as in Figure 3. We must combine two difference motions as given in Eq. (3) of the figure.
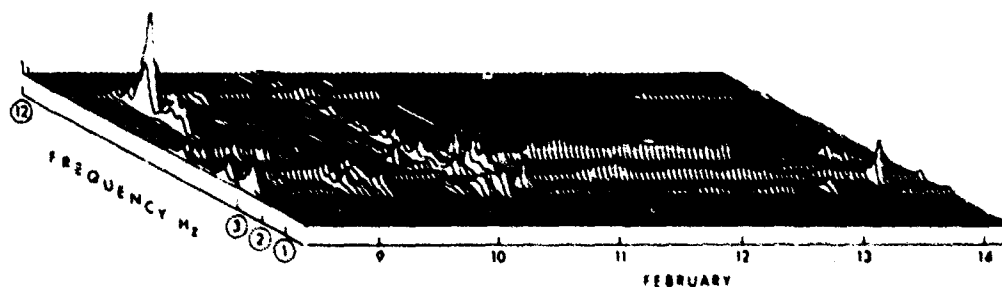

Figure 2. Spectrogram, ERC-NASA Site - Kendall Square, Cambridge, Mass. February 8-15, 1967

$$1)\ \frac{\partial u}{\partial y} \approx \frac{u_1 - u_3}{\Delta s} \qquad 3)\ \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = \psi \ (\text{ROTATION})$$

$$2)\ \frac{\partial v}{\partial x} \approx \frac{v_2 - v_4}{\Delta s} \qquad 4)\ \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} = \Sigma_{xy} \ (\text{STRAIN})$$
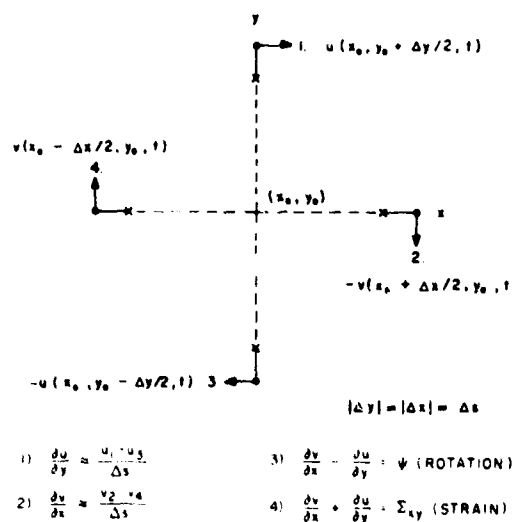
$$|\Delta y| = |\Delta x| = \Delta s$$

Figure 3. Seismometer Configuration for Rotation, Strain Measurements at the Honeywell Facility
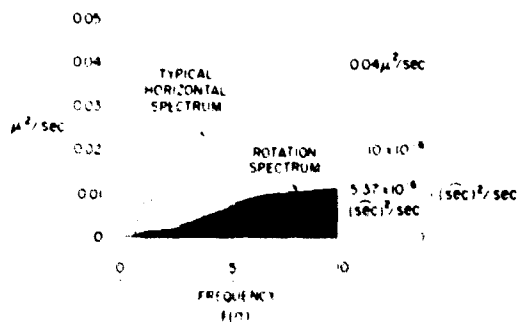

Figure 4. Total and Rotational Motion Estimates for the Honeywell Test

In principle, this technique presents no real difficulty; in practice, it requires highly matched transducers, because linear motions typically are much larger than rotations. Using this approach, we estimated rotation levels on stands now being used for ALS acceptance tests. Transducer matching was accomplished off-line using Wiener filters. The results of this experiment are given in Figure 4. Here, is shown the mean-square value of the linear and rotational motions as a function of bandwidth. Our approach appears to be adequate for estimating rotations when rotations approach bothersome levels.

Having discussed the mode of the motion, we now turn to estimates of component organization. Error terms introduced by nonlinearities in both gyros and pendulous accelerometers are affected by component motion relations. For the pendulum, the error is known as zero shift; for the gyro, this class of error is called coning or kinematic rectification. Estimates of coning error in an SDF gyro call for computing the cross-correlation between the components of stand rotations about the gyro's output and input axes. A considerable complication occurs in making coning error estimates if the stand motion is not a normal process, for then higher-order correlations and/or spectra must be determined.

The relations between component motions are conveniently revealed through coherency estimates, a measure of the strength of component relations under spectral decomposition. Our studies show the organization of the motion to be highly site-dependent. To illustrate (Figure 5), we find component relations are weak on Honeywell's ALS test stands. Here, the motion environment exhibits the
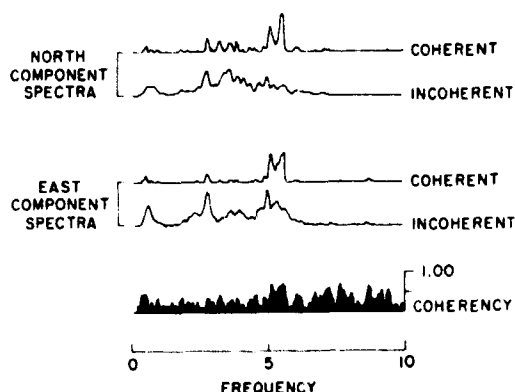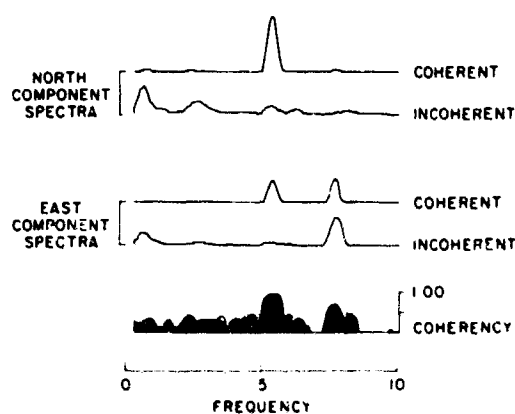
Figure 5.   Honeywell Motion Spectra
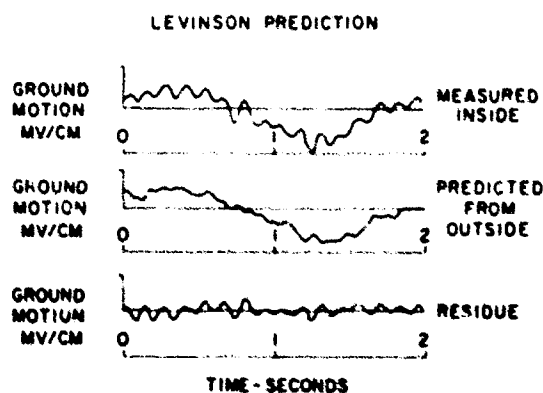

Figure 6.   Northrop Motion Spectra

LEVINSON PREDICTION

Figure 7.   Inside—Outside Motion (Time Domain)

attributes of an isotropic motion field, that is, the computed relations are the same as those that would result from a set of independent random motion sources uniformly dispersed around the measurement point. On the other hand, similarly treated measurements, taken at Northrop's test facility, Norwood, Mass., reveal that the motions at this test facility are highly organized (Figure 6). Indeed, when we use an optimum least-squares prediction to remove the motions caused by exterior sources, we find that motions excited by intra-plant sources are well related and concentrated around 8 Hz (Figure 7).

To summarize, in component testing a description of earth noise over the band 0.1 to 10.0 Hz calls for determining the following. (1) the class of the random motion; (2) its level; (3) the mode of the motion; (4) component relationships.

We would now like to turn to an experiment that removes earth noise error terms from gyro data. In effect, we treat the gyro as a multi-input single-output black box to earth noise inputs. The rationale of the experiment is outlined in Figure 8.

Figure 9 gives a sample relation between the gyro output and one of the component motions   The top portion of the figure is the measured gyro spectra. The darkened area at the base of this spectra
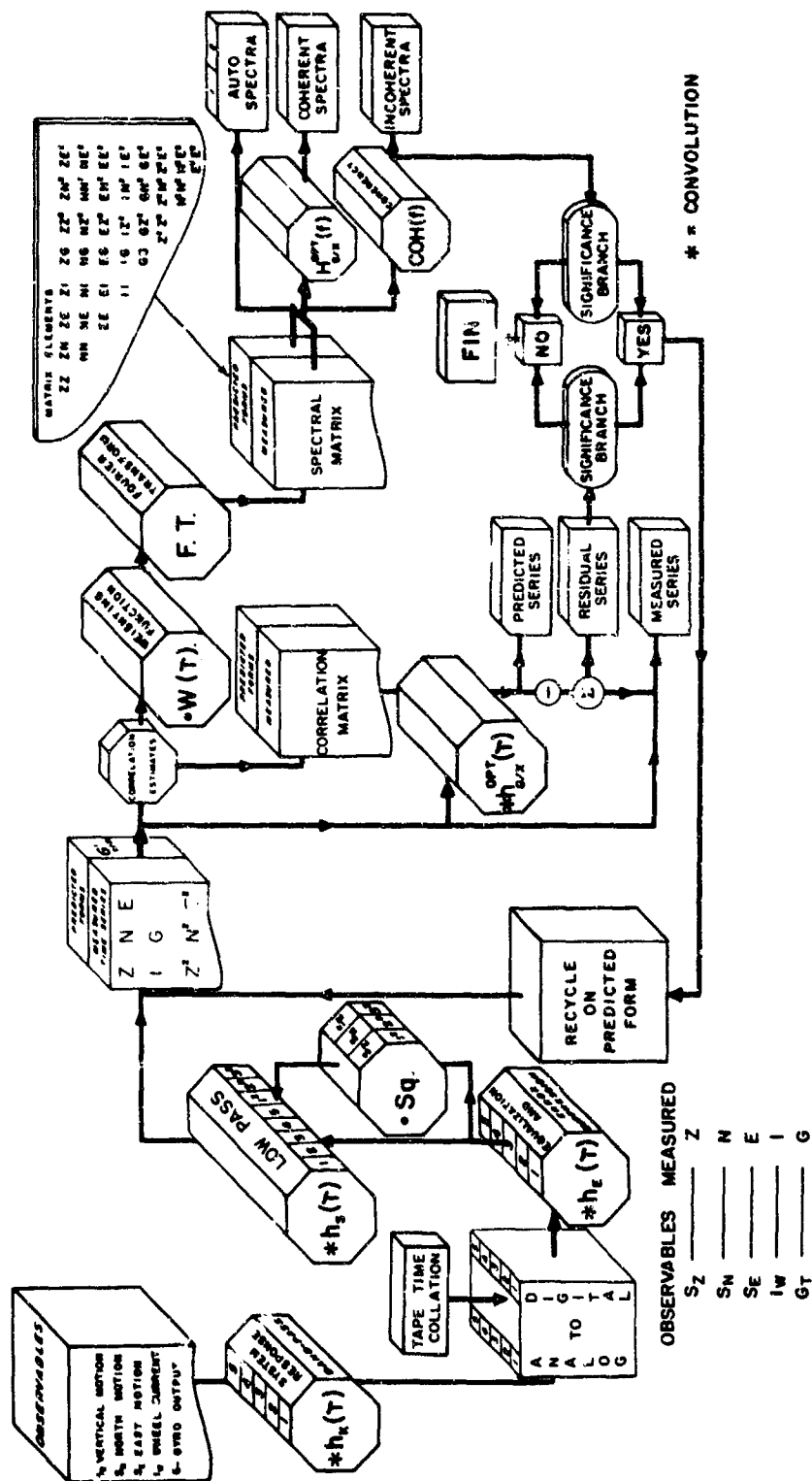
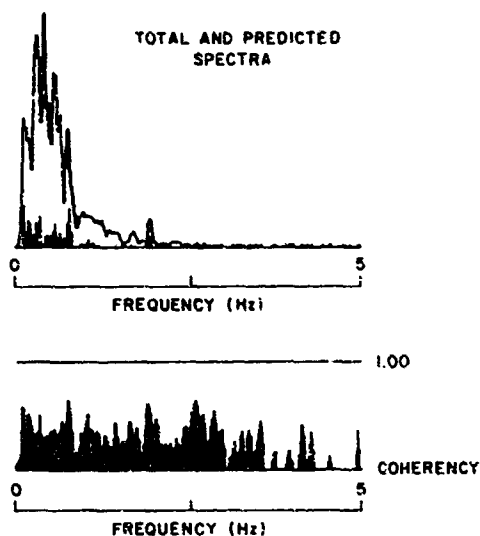Figure 8. Gyro-Seismometer Experiment Rationale

TOTAL AND PREDICTED
SPECTRA

FREQUENCY (Hz)

———————————— 1.00

COHERENCY

0   5

FREQUENCY (Hz)

Figure 9. Gyro Output Spectra Based
on Auxiliary Motion Estimates

TOTAL AND PREDICTED
SPECTRA

0   5

FREQUENCY (HZ)

———————————— 1.00

0   5

FREQUENCY (HZ)

Figure 11. Rectification
Prediction

OBSERVED
COHERENCE

β_ϵ (BANDWIDTH OF THE OBSERVED COHERENCE)-HZ

Figure 10. Significance
Level vs Resolution

is that portion of the gyro data that
can be removed by seismic measure-
ments, using a non-realizable Wiener
operator. The second element of the
figure is the coherency between the
data pair. In order to evaluate the
coherency plot, we must consider
levels of significance. Figure 10
gives the expected upper bound co-
herency estimate for the conditions
of our experiment vs bandwidth at a
1 percent level when the computed
coherencies are actually founded on
an uncorrelated data pair. The mea-
surements shown in the previous
figure (Figure 9) are barely signifi-
cant. In turn, Figure 11 is the co-
herency computed between accelera-
tions squared terms and the gyro out-
put. Here, the computed coherencies
are significant at well in excess of a
1 percent level. In our experiment,
we find we can remove something
like 50 percent of the low frequency
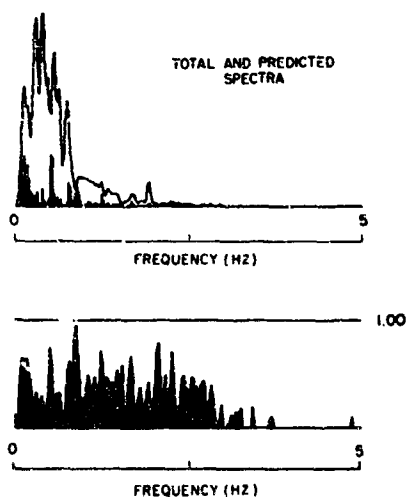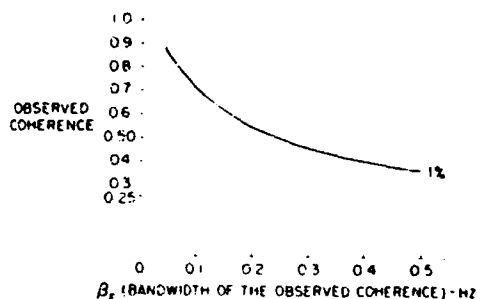content of the gyro output. Compliance in the gyro is known to lead to errors
sensitive to acceleration squared terms.

Heartened by this success, we have initiated a comprehensive long term ex-
periment to develop an estimate of the ultimate sensitivity of the SDF gyro used in

the ALS system when all environmental noise terms are removed. The experiment
is a joint effort by AFCRL and SAMSO. It will embrace all earth noise terms to
the extent that we can recognize and account for them, rather than just the 0.1 to
10.0 Hz motions, just discussed. The experiment, it is hoped, will have a marked
impact on the performance loss that too often occurs when we take a system out of
a contractor's laboratory environment into the field. It should also point the way
for better resolving between those errors due to earth noise and those due to hard-
ware deficiencies in future inertial component tests.

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F.A. Crowley
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A new method to approach earth noise field problems in inertial component testing is presented. This method is considered superior to accepted "quiet site" and "motion suppression structure" techniques. The approach is to describe earth noise by determining: (1) the class of the random motion; (2) the level of motion; (3) the mode of motion; and (4) the component relationships. The efficacy and rationale of this technique is demonstrated in an experiment that results in the removal of earth noise error terms from gyro data.

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